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Yawsonde Technology for the Jet Propulsion Laboratory (JPL) Free Flying Magnetometer (FFM) Program

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Abstract

The preliminary application of yawsonde technology to the Jet Propulsion Laboratory's (JPL) free-flying magnetometer (FFM) program has been completed. An optical sensor design has been completed specifically to meet the volumetric constraints of the JPL-FFM vehicle. Two sensor prototypes were fabricated, and one was extensively tested at the U.S. Army Research Laboratory. A review of yawsonde technology encompassing the optical sensors, installation within a flight vehicle, calibration, launch window simulation, flight testing, and data reduction is covered. The prospective sensor application is combined with projected solar ephemeris data and trajectory data to provide assurance of adequate coverage for projected flight tests. A data reduction methodology is developed wherein the sensors' orientation provides a means to determine solar aspect angle and solar roll rate of the vehicle.

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YAWSONDE TECHNOLOGY FOR THE JET PROPULSION LABORATORY (JPL)
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1. INTRODUCTION

The preliminary application of yawsonde technology to the Jet Propulsion Laboratory's (JPL) free-flying magnetometer (JPL-FFM) program has been completed. This program is projected to perform magnetic field mapping at extreme northern latitudes and high altitude. Since the orientation of the magnetometer with respect to earth is certainly required, yawsonde technology can aid in the determination of the inertial attitude through measurements of the in-flight angular position with respect to the sun. A complete yawsonde system includes the sensor design, sensor testing, installation and calibration, launch window simulation, flight with successful data acquisition, and data processing. Two sensor prototypes were fabricated, and one was extensively tested at the U.S. Army Research Laboratory (ARL).

The primary purpose of the ARL optical sensors is to provide a direct measurement of the relative attitude of a flight vehicle with respect to the solar vector. The solar aspect angle (σ) is defined as magnitude of the included angle between the roll axis and the solar vector, with both beginning at the center of gravity of the flight vehicle. Figure 1 depicts σ and its complement. The solar aspect angle is commonly referred to as the solar attitude or solar yaw angle. Sigma has a magnitude of zero when the spin axis is coincidental with the solar vector. The complement of σ, Sigma-N (σ_n), is also commonly used in related text and graphics.

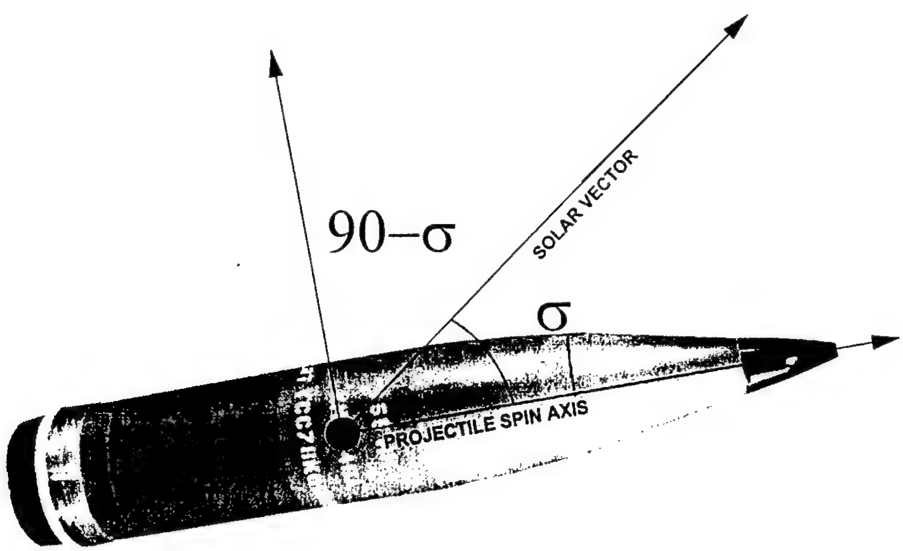

Figure 1. Definition of Solar Aspect Angle.

The further reduction of the solar attitude data to provide a solar roll history is an invaluable residual to the data reduction. The solar roll history is nearly equal to the spin rate of the vehicle for σ_n approximately equal to zero or for relatively low yaw and pitch rates.

2. OPTICAL SENSOR DESIGN

ARL has provided a number of sensor designs and installation configurations for a wide variety of flight vehicles that are a part of the U.S. Defense research and development needs. Several modifications of the sensor design, electronics, power supply, and packaging have recently resulted in a standardized configuration that interfaces directly with the current stock of tactical 155-mm inventory in a North Atlantic Treaty Organization (NATO)-compatible fuzed configuration. ARL maintains the capability to engineer sensors for particular flight vehicles; the JPL-FFM is one such candidate.

2.1 Sensor Design

Specific research designs, including the JPL-FFM, (see Figure 2) are engineered to be integrated into flight testing of development hardware to fulfill aerodynamic research requirements. The JPL-FFM sensor employs a new design of an optical slit with an obstructive pillar, smoothly curved reflectors and light-absorbing ridges, and a miniature silicon solar cell. The sensor is confined to a specific JPL-imposed external geometric constraint of 1.5 cm by 1.5 cm by 0.5 cm. The geometry and construction of the sensor are patent pending by the authors of this report.

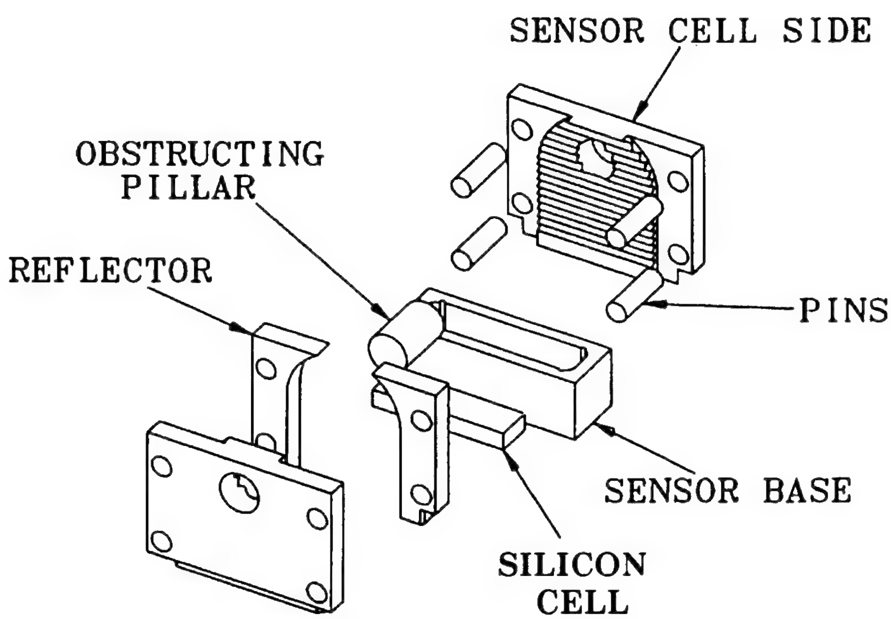

Figure 2. Assembly View of Prototype Sensor.

2.2 Prototype Sensor Testing

The electrical performance of the sensor is directly related to the sensor slit geometry. The current prototype sensor can supply as much as 250 mV into a 5-kohm (kΩ) load and has a 1-microsecond response capability. The sensor is a two-wire device that acts as a voltage or current source and requires no power. A photo-sensitive material combined with a mechanical slit comprises the basis for an indication of alignment of a sensor on a flight body with a fixed parallel light source. As light enters the slit, it is projected onto the cell surface, and an electrical output is produced. Ideally, the sensor geometry is a slit mask so that a maximum sensor output occurs within a theoretical half plane and no output occurs in any other plane.

In practice, the prototype geometry exhibits a field-of-view response similar to but certainly not equal to a half plane. The sensor prototype was tested in the orientation shown in Figure 3 with sensor output collected for rotation about each axis.

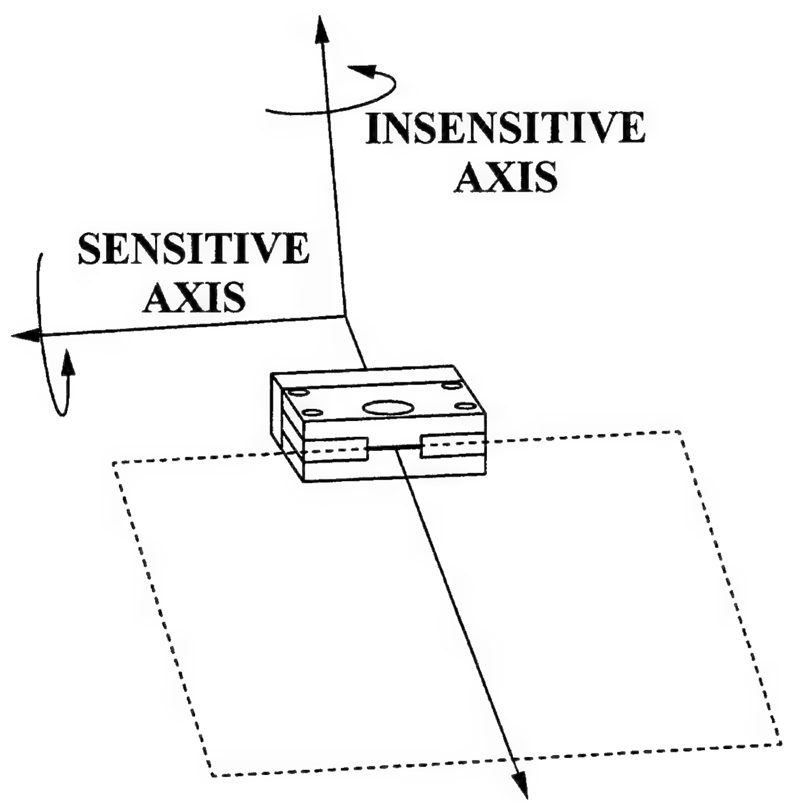

Figure 3. Theoretical Half-Plane of Sensor Alignment.

Figure 4 demonstrates typical rotation of the sensor about the sensitive axis. This provides a significant amplitude variation over an extremely narrow field of view (FOV). A 20% threshold is used to provide a reference FOV of less than ±2°.

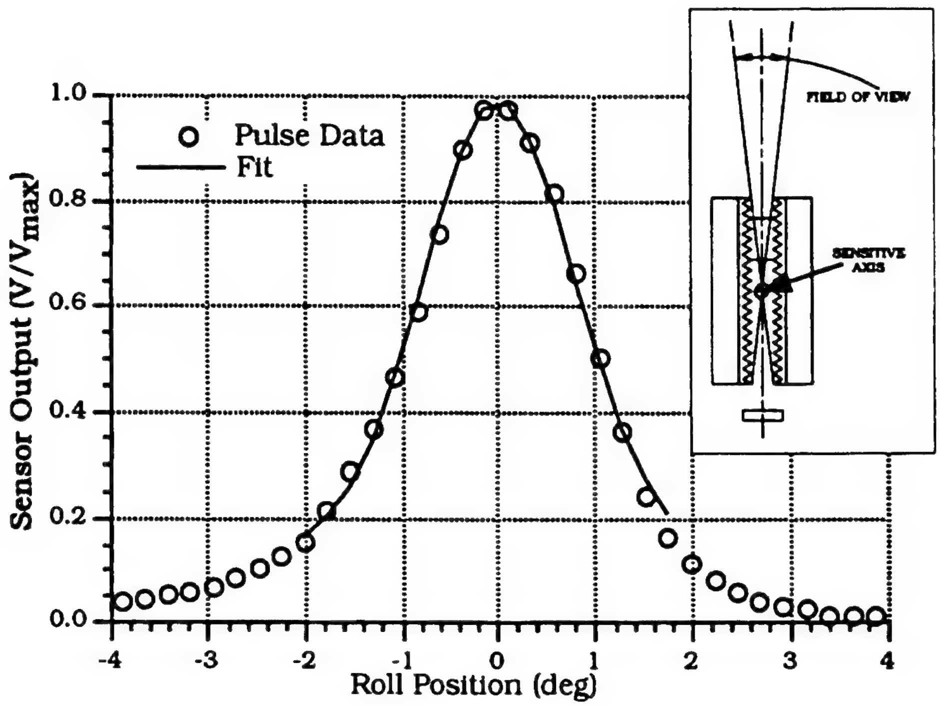

Figure 4. <u>Amplitude Variation for Rotation About the Sensitive Axis</u>.

The sensor slit is designed to minimize variation in output when rotated about the insensitive axis. Figure 5 shows an insensitive axis reference FOV of approximately ±85° for data above a reference level of 0.2. The combined FOV of both axes is within expected results and the sensor is deemed suitable for solar sensor alignment use.

Initially, the interior obstructive pillar was purposely manufactured undersized so that prototype testing could be executed for larger pillar diameters. Several iterations of increasing pillar diameters were required to compensate for initially unknown losses at the interior reflective surfaces. This remanufacturing of the first prototype caused the deviation visible from the empirical response in Figure 5. Unfortunately, it is clear that the larger obstructive pillar was no longer accurately located within the prototype sensor body. Subsequent manufacturing and testing of sensors with similar interior construction have shown no location tolerance sensitivity and verified the empirical response in Figure 5.

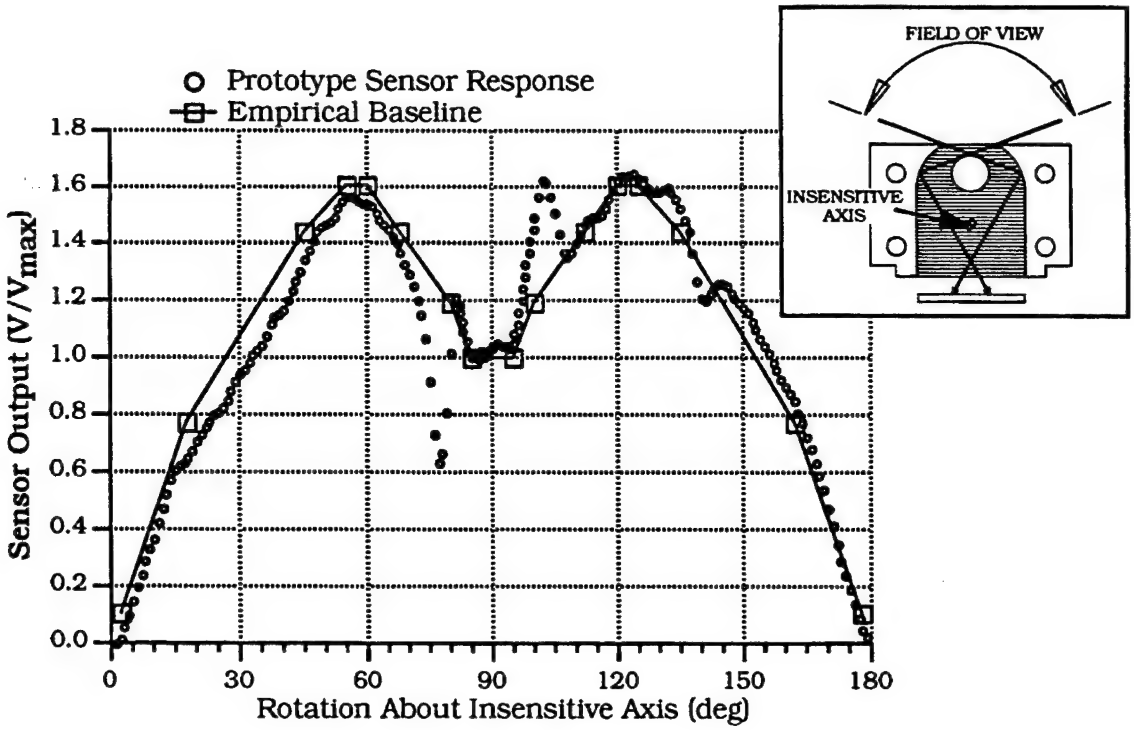

Figure 5. Amplitude Variation for Rotation About the Insensitive Axis.

3. SENSOR APPLICATION

Yawsonde technology employs the inherent spin of a vehicle and the resulting time-stamped measurements of the alignment occurrences of at least two body-fixed slits to a parallel light source. The sensor quantity (1,2..m), circumferential locations ($\phi_{1,2..m}$), and tilt angles ($\gamma_{1,2..m}$) are a function of the required resolution, trajectory and ephemeris data. A discriminant of the spin axis angle with respect to the solar vector can be generated for spinning vehicles with a minimum of two sensors with unequal tilt angles ($\gamma_1 \neq \gamma_2$). The tilting of sensors with respect to the body roll axis provides a means to reduce three consecutive sensor alignment occurrences into sigma. A phase angle, commonly called ratio, is used to determine the solar yaw angle by computing the phase relationship between consecutive sensor occurrences for both calibration and flight data.

3.1 Determining Sensor Quantity

Multiple optical sensor installations are governed by the geometric relationships for the quantity, location, and tilt angle only after the spin criteria is met. The Nyquist criterion of two samples per fast-mode yaw cycle allows a determination of the minimum number of sensors (m).

$$m \frac{\text{Spin Frequency}}{\text{Fast - Mode Frequency}} > 2$$

For example, the spin to fast-mode frequency ratio of 155-mm spin-stabilized projectiles can be estimated at about ten. Thus, the roll rate is high enough to sample the fast-mode projectile motion by using two sensors (m=2).

Slowly spinning vehicles with rapid roll rate changes may require more sensors to effectively increase the number of sensor occurrences in relation to the fast-mode motion. The FFM flight spin was given to be a constant 1000 rpm with no dynamic angular motion of the FFM [1]. Thus, the spin criterion is also met with just two sensors. In practice, two optical sensors are projected to be integrated into each FFM carrier. The sensor surfaces are exposed to the exterior surface and are machined to the conformal surface of the flight body.

3.2 Determining Orientation

A simulation of the expected roll position of peak response can aid in the installation design of multiple sensor installations. For a right circular cylinder, the solar roll position of alignment is a function of the circumferential location, tilt angle, and the solar aspect angle:

$$\phi = \phi_{0_m} - \sin^{-1}\left(\frac{\tan \gamma_m}{\tan \sigma}\right)$$

in which

ϕ_{0_m} = circumferential location of the sensor

γ_m = sensor tilt angle

σ = solar aspect angle

Since multiple sensor outputs are electronically summed, the simulation of multiple sensor installations allows a view of the overall peak response of the sensors to avoid superposition of the sensor outputs. The peak roll position location is shown in Figure 6 for diametrically opposed sensors with tilt angles of 0° and -30°. Placing the second sensor at a tilt angle of -30° allows a measurement range of approximately $40° < \sigma < 140°$ for a 170° sensor FOV and a 0.20 threshold.

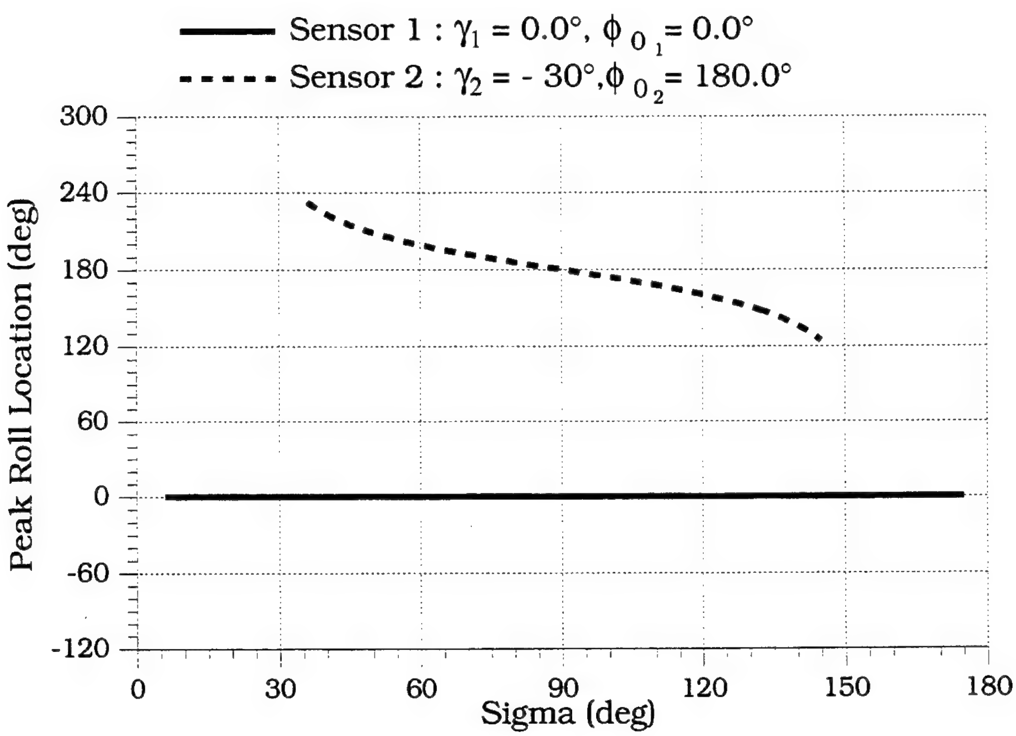

Figure 6. Theoretical Peak Roll Locations for Two Sensors on a Right-Circular Cylinder.

3.3 Sensor Calibration

After installation, manufacturing tolerances of the sensor and mechanical installation within a flight vehicle require calibration of the orientation of the sensor. Raw sensor data are acquired while a slow, steady roll is executed at a variety of fixed sigma values on a two-degree-of-freedom calibration table with an earth-fixed parallel light source. The digitized analog data are fitted against digital roll position data for each sensor occurrence to provide a tabular output of the peak occurrence roll position. The raw sensor data are fitted for peak position as a function of roll position.

$$\text{Sensor Output} = c_0 + c_1 e^{\{-[(\phi_s - c_2)/c_3]^2\}}$$

Coefficients c_0 and c_1 are a function of the sensor output and signal conditioning. The coefficient c_2 denotes the roll position of maximum sensor output and describes the roll position of slit alignment with the parallel light source. The coefficient c_3 is indicative of the pulse width and is a function of the slit geometry, tilt angle, and sigma.

Calibration of the multiple sensor system verifies the performance and installation. A look-up table of correlated roll positions and solar aspect angles of sensor alignment is generated. The

tabular data are fitted so that each sensor can be defined by the tilt angle and circumferential location. The calibration data can also be used to provide a look-up table of roll positions and non-dimensional phase angles for the transformation of sensor alignment times to sigma and solar roll-related derivatives.

4. LAUNCH WINDOW SIMULATION

Prospective sensor applications must be combined with solar ephemeris data and simulated trajectory data. Typical information that must be incorporated are date and time of launch, latitude, longitude, and inertial orientation angles (elevation and azimuth of fire). Additional data that should be included within the attitude data are the pitch and yaw histories about the nominal trajectory. The spin data must be supplied to confirm the Nyquist criteria for minimum sensor quantity. The proper design of a yawsonde system may also need to incorporate the variations in nominal trajectory that are attributable to launch disturbances and potential instabilities. Delays in test scheduling coupled with seasonal solar vector changes may also require consideration. Simulated flight data were provided by JPL **[2]** and used by ARL to ensure the yawsonde application was both practical and meaningful.

4.1 Solar Aspect Angle Simulation

It is assumed that the FFM carrier launch will occur at Poker Flats, Alaska, on February 1, 1999. Since the current FFM flight parameters are zero order in nature, the FFM attitude is assumed equal to the carrier rocket at the time of ejection and remains unchanged for the duration of the flight. At 140 seconds, the inertial elevation is estimated at 70° and the azimuth is estimated at 4°. No launch disturbances or dynamic motions are modeled. Solar vector data are combined with the fixed inertial attitude to provide the launch sigma as a function of local launch time (see Figure 7). Comparison of the flight measurements with this reference sigma will yield the FFM attitude variation in the solar yaw plane.

4.2 Launch Window Determination

While it is clear that the simulated FFM attitude is within the measurement capability, it has not been ascertained whether the solar vector is available to illuminate the FFM. Thus, the window for full solar coverage must be established. The range and altitude data are shown in Figure 8. Sigma and roll data are to be collected for altitudes exceeding the ejection altitude of 275 km **[1]**. The flight time of interest extends from 140 to 925 seconds.

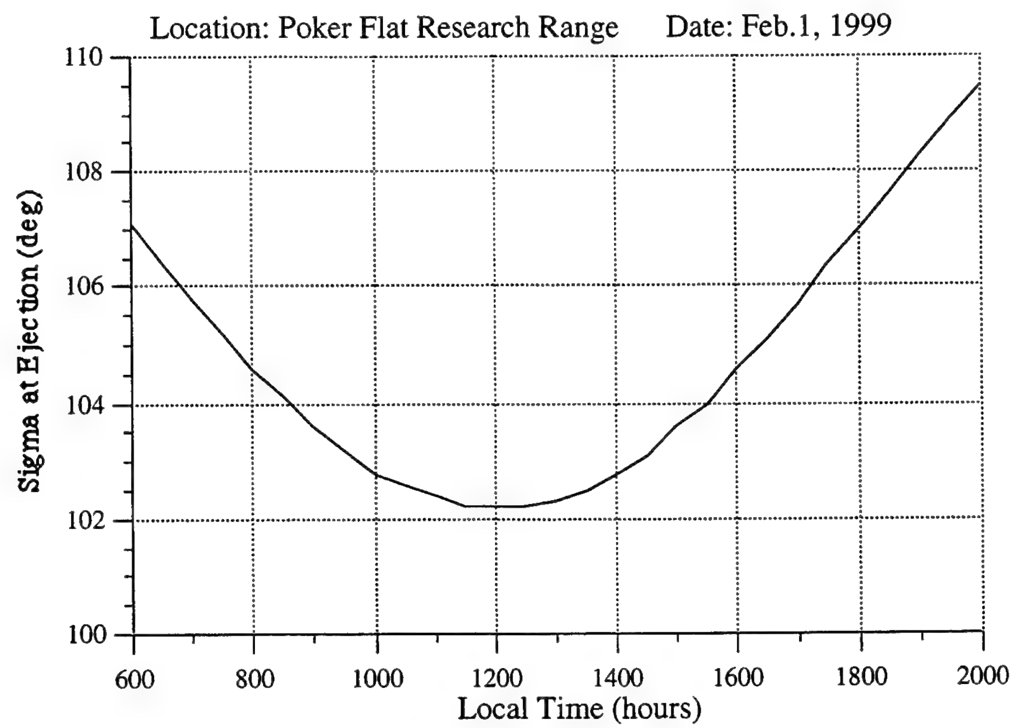

Figure 7. FFM Sigma Simulation at Ejection.

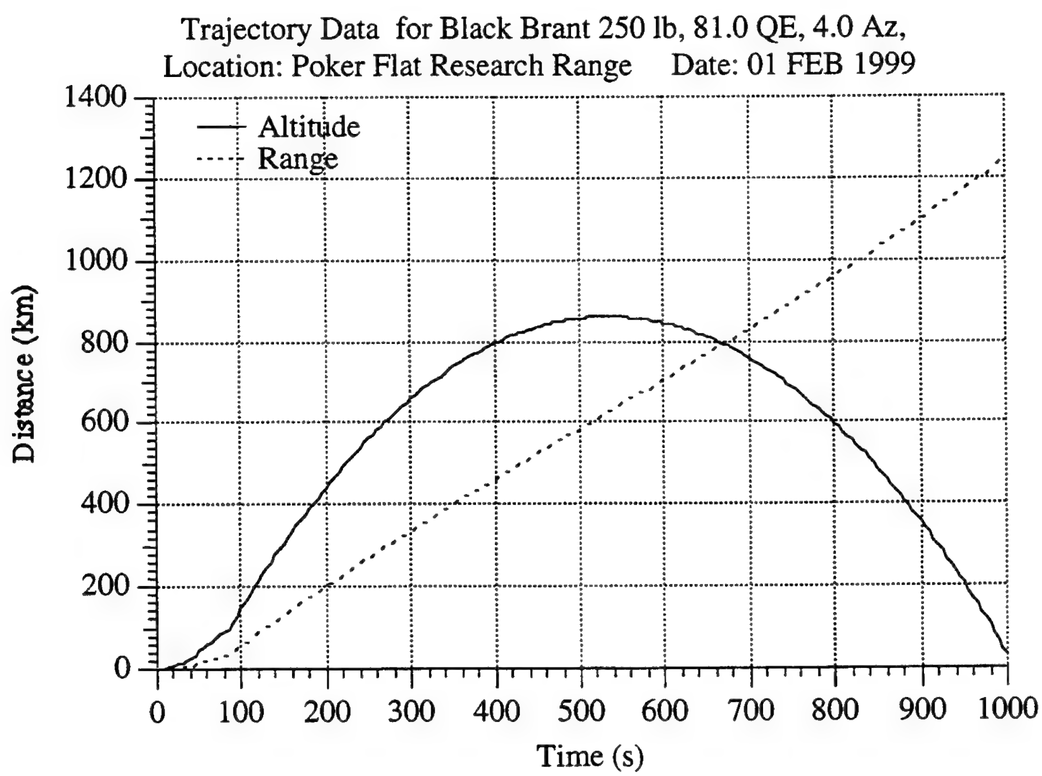

Figure 8. Trajectory Data for FFM Carrier Rocket.

The projected solar elevation data with respect to local horizontal are shown in Figure 9 for the carrier at the launch, midway, and impact points. As expected, it is clear that a very small amount of time is actually available for solar illumination if the altitude of the FFM is 0.0 msl. The high altitude flight of the FFM provides additional solar visibility via the dip angle **[2]**. Figure 10 indicates the dip angle from the FFM local inertial horizontal to the horizon at each trajectory simulation point. The dip angle at 275 km is -16.5°. Solar elevations above -16.5° (in Figure 9) allow sunlight onto the FFM throughout the flight time of interest. Thus, the preliminary full solar coverage window for carrier launch times can be determined as 0700 to 1830 local time.

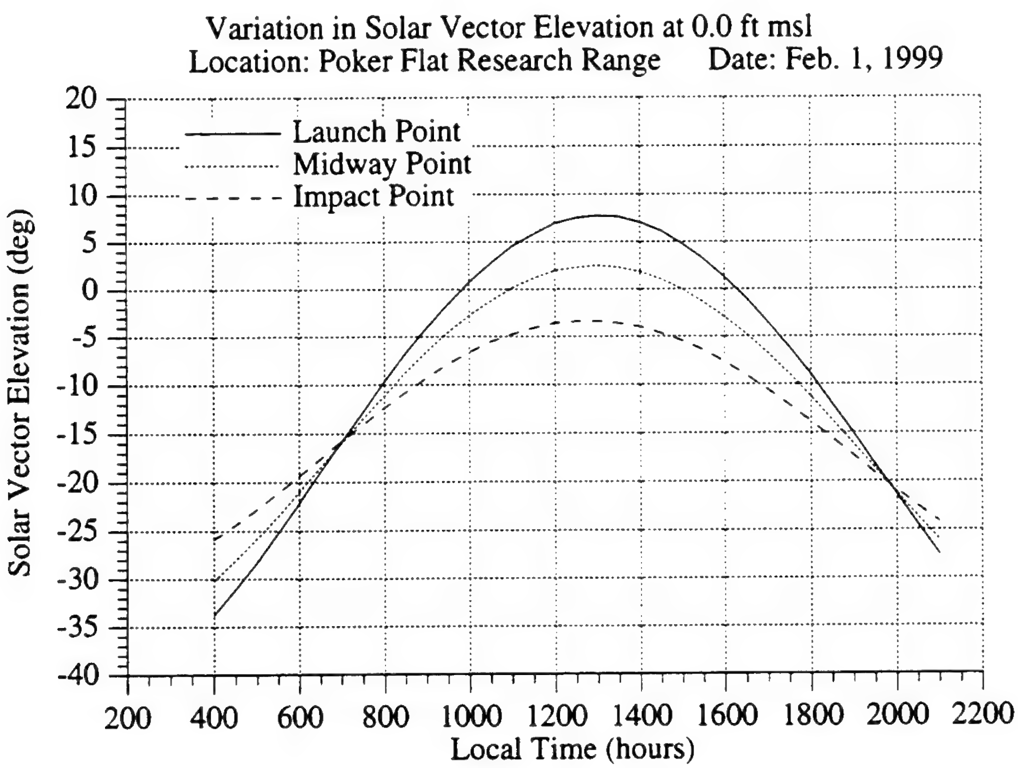

Figure 9. Solar Vector Elevation at Mean Sea Level.

5. DETERMINING SOLAR ASPECT ANGLE

Ultimately, the FFM vehicle will be launched with a yawsonde system aboard within the launch window and with meteorological conditions conducive to sunshine. The sensor data can be stored on board and recovered or transmitted back to a ground station. Two methods of data collections are used for telemetry applications: analog data via FM/FM or digital data via pulse code modulation (PCM).

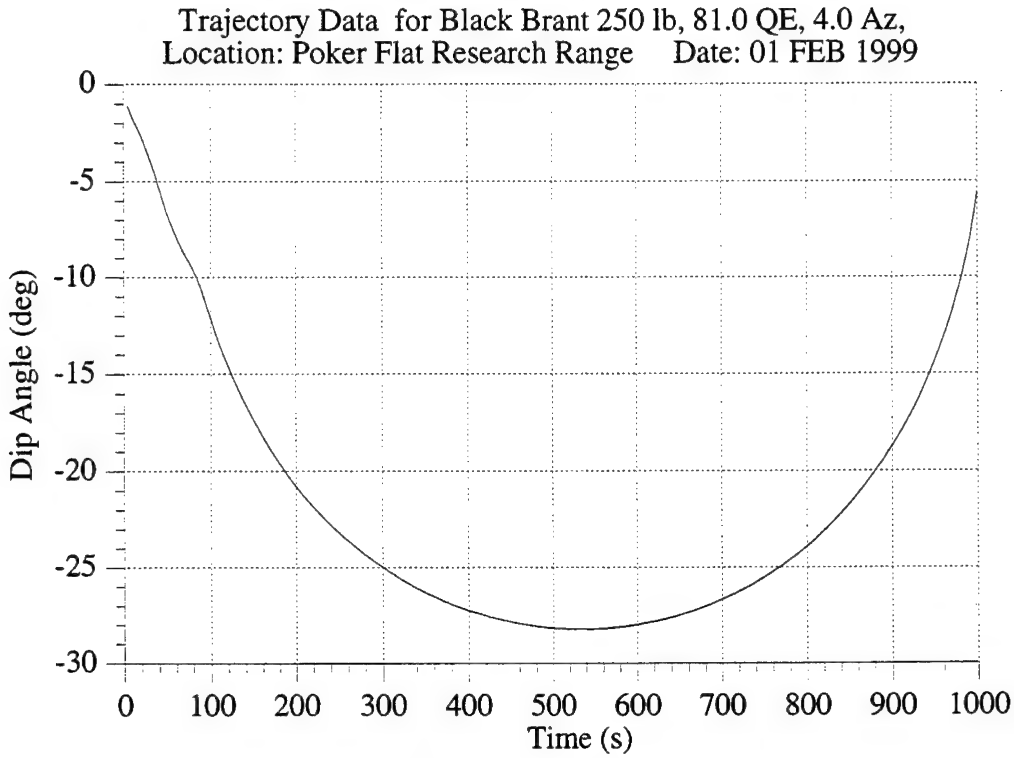

Figure 10. Dip Angle.

Analog applications include FM/FM telemetry using high frequency voltage-controlled oscillators. A stream of analog pulse data is telemetered during flight. Analog reduction techniques employ ground-based analog-to-digital conversion and curve fitting to determine the peak occurrence time. Analog applications use sensor output polarity and/or amplitude levels to identify sensor output.

Digital applications primarily use on-board PCM systems that can digitize the entire raw data trace for telemetry. Advanced digital applications transmit the leading and trailing edge detection times. These are averaged to provide a slit alignment time with a very low telemetry bandwidth requirement.

Finally, the sensor identification ($s_{1,2...n}$) and the sensor occurrence alignment times ($t_{1,2...n}$) for the quantity (n) of solar alignment occurrences are tabulated. A standard methodology is reviewed so that solar aspect angle and roll rate can be extracted. The raw data are routinely reduced and verified via advanced reduction routines at ARL to verify the applicability of this standardized routine. Advanced reductions are substituted when appropriate, including but not limited to compensation for varying solar angle or roll rate. All available data are collected,

archived, and can be reduced in the field environment to enhance the flexibility of the test requirements. Data are archived and disseminated to interested parties.

5.1 Solar Aspect Angle Measurement

Historically, two constraints have dominated the reduction of three consecutive yawsonde sensor occurrence times to a sigma history:

a. The solar roll rate is constant for three sensor alignment occurrences.

b. Sigma is constant for three sensor alignment occurrences.

Constraints a and b are applicable for any stable, spinning vehicle where the solar attitude and roll rate are slowly varying. Advanced reduction techniques have been further implemented to compensate for rapid roll rate changes and/or rapidly varying sigma.

The following variables are defined the standard reduction:

σ - included angle between projectile spin axis and solar vector.
ϕ_S - solar roll angle of projectile spin axis.
θ - non-dimensional phase angle (commonly called ratio).

Following restrictions a and b, the commonly used formula for the computation of ratio (θ) can be developed. The solar roll acceleration, roll rate, and roll position for three consecutive sensor occurrences are noted.

$$\ddot{\phi}_{s_{n-1,\,n,\,n+1}} = 0$$

$$\dot{\phi}_{s_{n-1,\,n,\,n+1}} = a_1$$

$$\phi_{s_{n-1,\,n,\,n+1}} = a_0 + a_1 t_{n-1,n,n+1}$$

The calibrated roll position of the center alignment occurrence between the adjacent occurrences can be expressed as a non-dimensional phase angle (θ).

$$\theta_n = \frac{\phi_n - \phi_{n-1}}{\phi_{n+1} - \phi_{n-1}}$$

$$\theta_n = \frac{a_0 + a_1 t_n - a_0 - a_1 t_{n-1}}{a_0 + a_1 t_{n+1} - a_0 - a_1 t_{n-1}}$$

$$\theta_n = \frac{t_n - t_{n-1}}{t_{n+1} - t_{n-1}}$$

Thus, θ computed from solar alignment times corresponds to a one-to-one mapping with θ calculated from calibrated peak position data at any constant sigma. The theoretical range of ratio is shown in Figure 11 for the projected JPL-FFM configuration. Thus, the non-dimensional phase angle of each sensor in time is transformed into the solar aspect angle, σ.

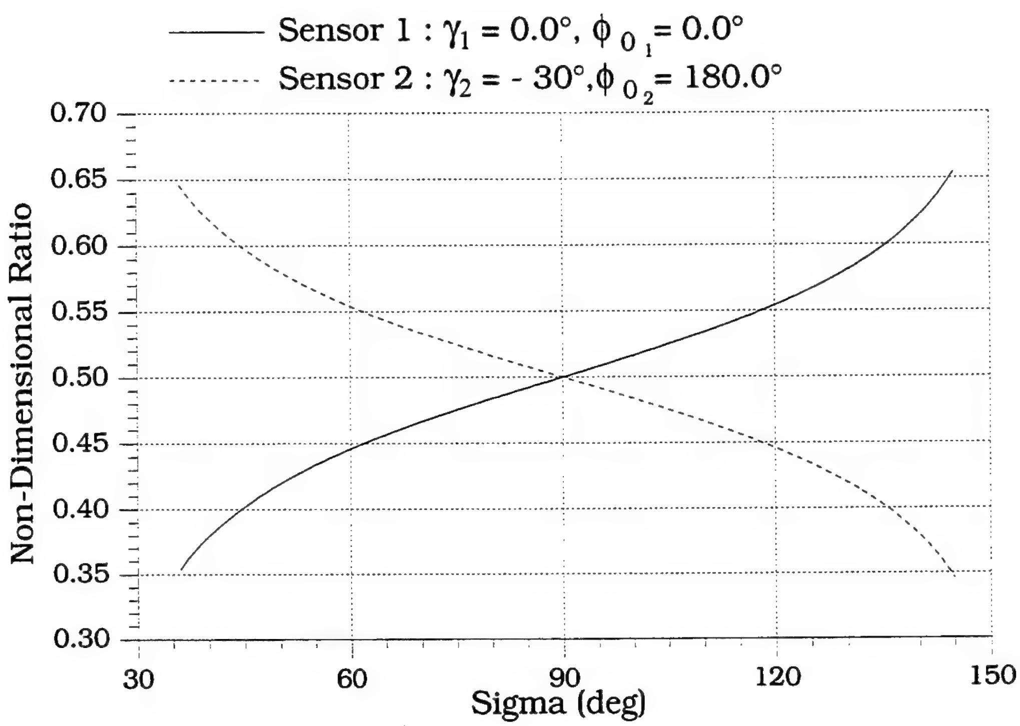

Figure 11. Theoretical Non-dimensional Ratio Versus Sigma.

5.2 Solar Roll Rate Measurement

The current standard of yawsonde reduction yields an indication of the spin rate of a flight body through the use of the solar roll position and related derivatives solar roll rate and solar roll acceleration. For each solar occurrence time and solar aspect angle, the calibrated roll positions ($\phi_{1,2...m}$) are assigned using the sensor identification to produce a flight history of sensor roll positions ($\phi_{s1,2...n}$). The sensor roll position data are accumulated to provide an indication of the

total number of revolutions since launch, thus providing a solar roll position history. A numerical central difference for interior points, forward difference for the first point, and backward difference for the last point are applied to both the accumulated solar roll position and the unequally spaced time data. The rate of change of the roll position with respect to the rate of change of sensor occurrence times yields the solar roll rate.

The solar roll rate and the spin rate of a vehicle are related closely when sigma is near 90° and/or when the yaw and pitch rates are relatively low when compared to the spin rate. The current JPL-FFM model suggests no angular dynamic behavior at all; hence, the solar roll rate is a good metric for the spin rate of the vehicle. Analysis of actual flight data or detailed simulation data can provide a measure of validity of the spin approximation.

6. CONCLUSIONS

The preliminary application of yawsonde technology has been completed for the FFM flight test program. A sensor design and installation configuration combined with trajectory and ephemera data ensures a successful measurement scenario. Cooperative efforts involving manufacturing, testing, advanced trajectory simulations, data simulation, and advanced data reduction techniques are required to further the yawsonde application.

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2. Cutting, E. Correspondence by mail, April 1997.

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13. ABSTRACT *(Maximum 200 words)*

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